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RESEARCH PAPER 71  
1962

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# PROJECT SKYFIRE PROGRESS REPORT, 1958-1960

by

**DONALD M. FUQUAY**

DIVISION OF FOREST FIRE RESEARCH



INTERMOUNTAIN FOREST & RANGE EXPERIMENT STATION

FOREST SERVICE

U. S. DEPARTMENT OF AGRICULTURE

OGDEN, UTAH

JOSEPH F. PECHANEC, DIRECTOR



Research Paper 71  
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U.S. Department of Agriculture  
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## FOREWORD

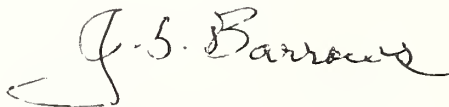
This report summarizes Project Skyfire lightning research for the period 1958 through 1960. Several reports on specific problems within the scope of the project have been published, but no general report has been made of the research program nor of the special instruments and techniques used on the project. This report describes research aims, experimental design, results of studies of lightning storm characteristics and of the effect of cloud seeding on lightning occurrence.

The following persons participated in the research program and in preparation of this report:

Donald M. Fuquay, Project Leader  
Robert G. Baughman, Research Meteorologist  
Clyde A. O'Dell, Research Meteorologist  
Dr. Howard E. Reinhardt, Mathematical Statistician (part time)  
Alan R. Taylor, Research Forester (part time)  
Howard J. Wells, Meteorological Aid (part time)  
Ivalou O'Dell, Meteorological Aid (part time)  
William H. Everard, Electronic Technician (part time)

This research has been carried out in cooperation with several agencies. We are indebted to Dr. Gilbert Kinzer, Director, Physical Sciences Laboratory, U.S. Weather Bureau, for the loan of equipment and for invaluable counseling on all phases of the project. Agencies aiding in the collection of data include National Forest Administration, the National Park Service, and the U.S. Weather Bureau.

The project greatly appreciates the work of summer field assistants, whose initiative and diligence under adverse field conditions contributed immeasurably to success of the program.

A handwritten signature in dark ink, reading "J. S. Barrow". The signature is written in a cursive style with a large, sweeping initial "J" and a long, horizontal flourish extending to the right.

Chief, Division of Forest Fire Research

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## PROJECT SKYFIRE

### PROGRESS REPORT 1958-1960

#### I. INTRODUCTION

Fires started by lightning cause severe damage to commercial timber and to the watershed, wildlife, and recreation values of forest land. During the 20-year period, 1939-1958, lightning caused more than 132,000 fires in the 13 western states including Alaska. About 7,500 lightning-caused forest fires occur annually in the United States. In the western United States, lightning is the most frequent single cause of forest fires; in the Rocky Mountain states, 70 percent of all forest fires are lightning caused.

During one 10-day period in July 1940, the National Forests in western Montana and northern Idaho reported 1,488 lightning fires. In this period, 335 lightning fires occurred in one 24-hour period. Ability to cope with the greatly increased workload caused by such an outbreak often determines the degree of success attained by a fire control organization. Any method of reducing the number of lightning fires would have great economic importance. Of special importance would be a method for reducing peak numbers of lightning fires started by a single storm system.

Project Skyfire, conducted by the U.S. Forest Service, is a study of meteorological problems associated with lightning-caused forest fires. The project has two long-range objectives: (1) to obtain better understanding of the occurrence and characteristics of lightning storms and lightning fires in the northern Rocky Mountain region, and (2) to investigate the possibility of preventing or reducing the number of lightning fires by applying techniques of weather modification.

#### II. BACKGROUND

A regionwide survey of the occurrence of thunderstorms and lightning discharges was begun in 1955 and is still in progress. Visual observations are made by forest fire lookouts located throughout Montana, Idaho, northeastern Washington, eastern Oregon, and northwestern Wyoming (Barrows et al. 1957). This survey has produced considerable information about the frequency of lightning and other thunderstorm characteristics.<sup>1</sup> Several research papers based on data from this regionwide network are planned for publication.

Exploratory cloud-seeding operations started in 1956 demonstrated the need to develop cloud seeding and other research equipment that could be used in mountainous regions for cloud physics studies. Consequently, new airborne and ground-based silver iodide smoke generators were developed and field tested. As a part of the program of equipment development, a technique was devised for calibrating generators in the field (Fuquay 1960).

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<sup>1</sup> Fuquay, Donald M. 1959. Some thunderstorm statistics for the northern Rocky Mountain region. Intermountain Forest and Range Expt. Sta., U.S. Forest Service. Unpub. manuscript presented at the Skyline Conference on the design and conduct of experiments in weather modification. 22 pp., illus.

In the summer of 1957, a test area was established in the Lolo National Forest near the summit of the Bitterroot Range along the Idaho-Montana border. A field experiment was designed to study dispersion of silver iodide crystals from a network of ground-based generators and to observe the effect of silver iodide on cumulus clouds.

The invisible silver iodide smoke plumes were traced by using a portable cold chamber mounted in a light aircraft. The objective was to measure the number of silver iodide crystals entering cumulus updrafts at various distances downwind from generator sites. The aircraft made successive traverses at about 5-mile intervals downwind from the generators at an elevation of 10,000 feet or at cloud base, whichever was lower. Substantial numbers of nuclei were observed only in regions of updrafts.

Surface weather conditions strongly influenced dispersion of silver iodide. When the air was stable near the surface, virtually no crystals were carried to cloud base level. Drainage winds complicated the dispersal patterns of silver iodide crystals. Silver iodide was traced on the surface as far as 20 miles from the source in the general downwind direction when drainage winds were present. A cold box mounted in an automobile was used to trace the smoke. Dispersion was further complicated by silver iodide being carried 8 to 10 miles along the valley floors in a direction opposite to the wind flow over the ridges. Silver iodide proved to be so good a tracer for surface wind studies that this equipment was subsequently used to trace the extent of down-valley winds (Schaefer 1957). Lloyd, O'Dell, and Wells (1959) used this method to trace the route of the airborne sporidia of blister rust (Cronartium ribicola Fischer) into a plantation of western white pine (Pinus monticola Dougl.).

The plume-tracing experiments showed that silver iodide particles released from ground-based generators were dispersed in wide and virtually unpredictable patterns under certain meteorological conditions. Wind, atmospheric stability, and terrain all strongly influenced the dispersal pattern. It was concluded that necessary conditions for controlled-area experiments could not be met in mountainous regions with ground-based generators.

Measurements of nuclei concentrations downwind from the generators made possible a first approximation of the photo-deactivation of silver iodide crystals due to sunlight. Two methods were employed to compute the rate of deactivation. The first method assumed that total generator output ( $10^{13}$  nuclei per second per generator effective at  $-20^{\circ}$  C. was homogeneously mixed through all layers from 5,000 feet to cloud base. The plume volume was computed from the measured width of the plume and the radial distance from the generators. The computed concentrations at various points within the volume were compared with measured values at the same point. The second method involved calculation of the silver iodide decay independently of generator output. A measured concentration in the plume was followed downwind to a second measured concentration. The second concentration was assumed to have been decreased from the first by plume divergence and the decay of the silver iodide. Results from this method agreed with those from the first method.

Decay rates computed from 37 observations (fig. 1) were as follows: 76 percent of the observations showed a decay rate of less than 2.5 orders of magnitude per hour; 73 percent were less than 2 orders per hour; 62 percent were less than 1 order per hour. The nuclei exposed to sunlight longer than 30 minutes usually showed a decay rate considerably less than 1 order of magnitude per hour.

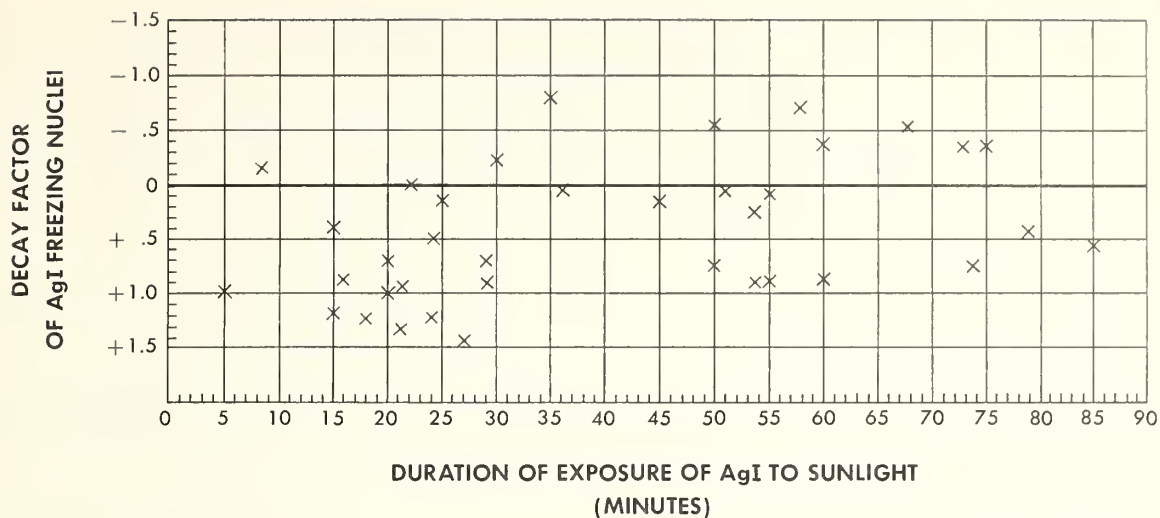


Figure 1.--Measured rates of photo-deactivation of silver iodide crystals in free air.

### III. STUDIES OF THUNDERSTORM AND LIGHTNING CHARACTERISTICS

Forest fire lookouts participating in the regionwide lightning survey were trained to obtain information on the formation and movement of thunderstorms, and on the frequency of lightning discharges. Thunderstorms and lightning statistics in this section of the report were compiled from data taken by lookouts during the period 1955-1958.

The average annual number of thunderstorm periods for July and August 1955-58 as reported by the Skyfire lookout network is shown in figure 2. It illustrates the wide variation characteristic of mountainous country. For example, Gisborne Mountain (Skyfire Station No. 2) in northern Idaho reported an annual mean of four thunderstorm periods, while Chewela Lookout (Skyfire Station No. 3), located about 50 miles west of Gisborne Lookout in north-eastern Washington, reported 16. Such variation is common in the Rocky Mountain region.

Annual numbers of thunderstorm periods and cloud-to-ground lightning discharges reported by the Skyfire stations are shown in table 1.

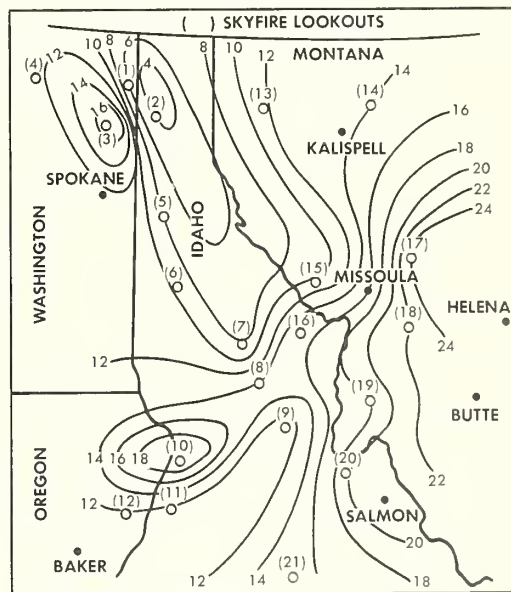


Figure 2.--Average annual number of thunderstorm periods for July and August 1955-58, as reported by Skyfire lookout network. Numerals in parentheses are station designators.

Table 1.--Thunderstorm periods and cloud-to-ground lightning discharges,  
July-August 1955-58

Year	: : Reporting : stations	: : Storm : periods	: Cloud-to-ground : discharges	: Discharges per : storm period
1955	16	178	6,026	34
1956	22	335	10,047	30
1957	22	238	4,355	18
1958	21	276	6,988	25
	Total	1,027	27,416	107
	Average	257	6,854	27

Duration of these 1,027 storm periods reported by Skyfire lookouts is shown in figure 3. The term "storm duration" or "storm period" is defined as the period of generally continuous thunderstorm activity within a 20-mile radius of the lookout, beginning with the first lightning discharge and continuing until the last. The grouping of storm duration by 30-minute intervals indicates that about one-half of all storms last 30 to 90 minutes, but only 15 percent of the storms continue less than 30 minutes.

The cloud-to-ground lightning discharges reported here were flashes actually seen by lookouts. The ability of a lookout to see and identify lightning flashes may vary according to the type and location of the storm. Comparison of total lightning observed by a lookout with field meter records indicates that on relatively isolated storms, the lookout apparently can see 80 to 90 percent of the cloud-to-ground flashes. During intense widespread storms where visibility is limited, the observer may count only 25 percent of the flashes. We believe that over a long period a lookout will see about one-half of all cloud-to-ground flashes occurring within his designated area. The reader is cautioned to bear this in mind when comparing these data with lightning frequency information derived from other sources.

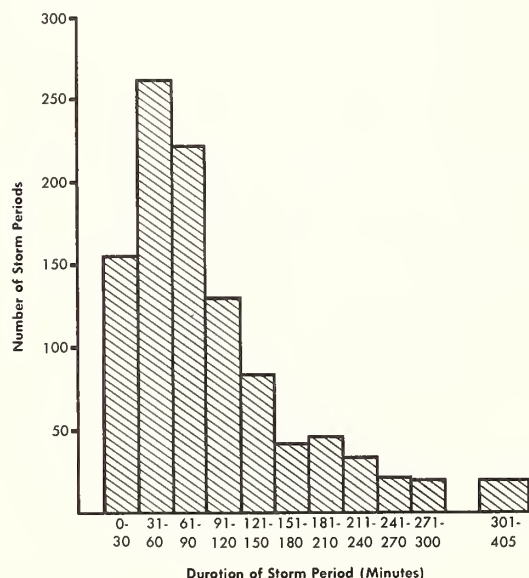


Figure 3.--Frequency distribution of thunderstorm periods in July and August 1955-58, classified by duration of storm period, as reported by Skyfire lookout network.

The distribution of these storms by cloud-to-ground discharge frequency intervals is shown in figure 4. Nearly half of the storms had fewer than 10 discharges, and about 70 percent had fewer than 20 discharges. Only about 5 percent of the storms had more than 100 cloud-to-ground discharges.

About 50 percent of the 1,027 storm periods reported had fewer than 10 lightning discharges to ground. However, this storm class contributed only 10 percent of the total

number of discharges to ground. The storms for which more than 100 ground discharges were reported per storm contributed about one-third of the total number of discharges. The percentage of total cloud-to-ground discharges per storm is shown in figure 5.

The mean annual discharge density over large regions is of particular interest to workers in atmospheric electricity since the charge transferred by cloud-to-ground discharges has been postulated as the mechanism for maintaining the electric field in the atmosphere. The mean annual number of cloud-to-ground discharges per 1,000 square miles occurring in July and August is shown in figure 6. A mean annual density of 200 discharges, based on 4 years of records, is shown for the Skyfire test area southwest of Missoula, Montana.

This study revealed the following general characteristics of lightning storms in the northern Rocky Mountains:

1. The average number of lightning storm periods per National Forest per fire season varied from a low of four in areas of relatively infrequent occurrence to a high of 24 in severe lightning areas.

2. Most lightning storm periods were relatively short. About half of the storm periods lasted for 30 to 90 minutes, and some 15 percent of the storms lasted less than 30 minutes. Only 4 percent continued longer than 300 minutes.

3. Many storms produced a relatively low number of cloud-to-ground discharges. Records showed that about 50 percent produced 10 or fewer discharges to ground. The 5 percent of storms that produced more than 100 discharges per storm accounted for more than one-third of the discharge total for all storms.

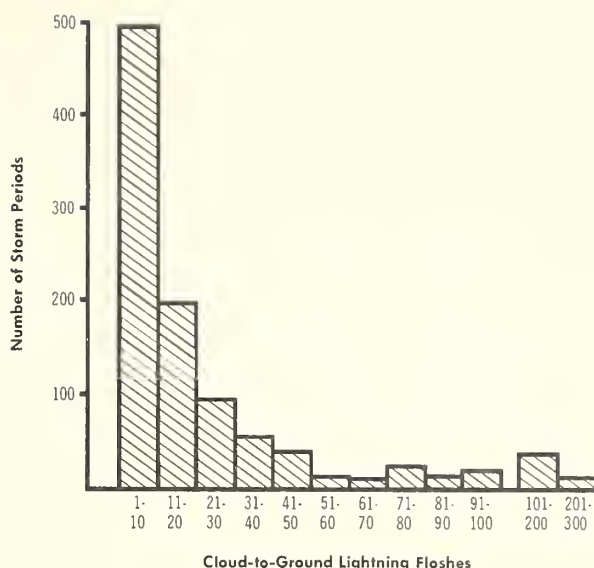


Figure 4.--Frequency distribution of thunderstorm periods in July and August 1955-58, classified by number of cloud-to-ground lightning discharges per storm (based on 1,027 storm periods).

Figure 5.--Percentage of total cloud-to-ground lightning discharges contributed by storms classified by number of cloud-to-ground discharges per storm. The inside scale on vertical axis shows number of discharges corresponding to percentage values.

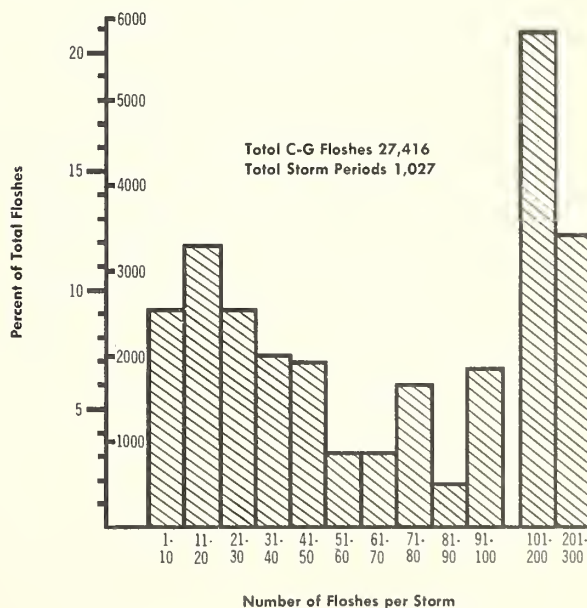
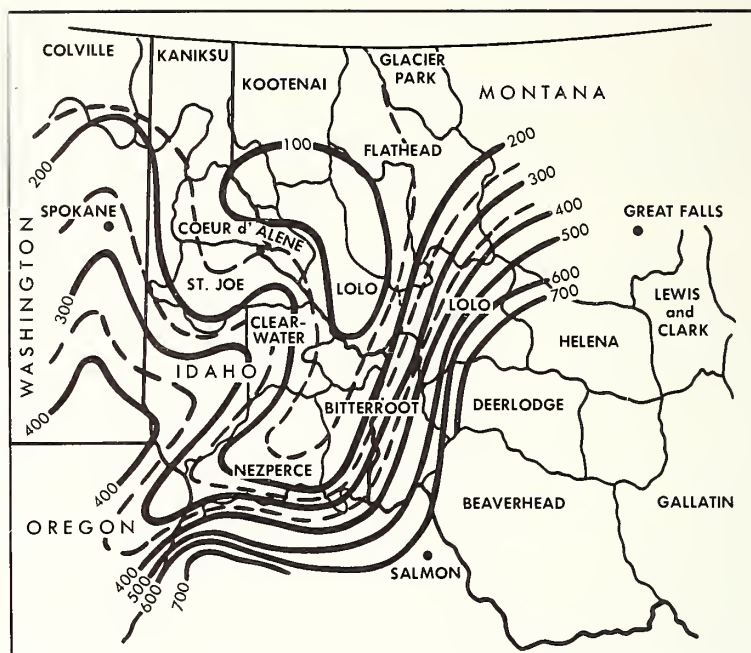


Figure 6.--Average annual number of observed cloud-to-ground lightning flashes per 1,000 square miles reported by Skyfire lookout network, July and August 1955-58.



4. Many lightning storms yielded little precipitation. During a 4-year period, about 50 percent of the storms produced less than 0.1 inch of precipitation. Another 20 percent produced from 0.1 to 0.2 inch of precipitation.

5. About 20 percent of all storms yielded precipitation as hail or graupel.

6. Lightning storms observed in western Montana had high cloud bases and were relatively shallow in total height. The average cloud base was near 12,000 feet m.s.l. Active dry thunderstorms were observed with bases nearly 17,000 feet above sea level. Average cloud base temperature was near the freezing level.

#### IV. STUDIES OF LIGHTNING STORM MODIFICATION

In recent years many workers have speculated on the possible effects of cloud seeding on precipitation, hail, lightning, thunderstorm downdrafts, and all major-scale weather phenomena. The anticipated results are often purely speculative since there is usually no clear understanding of the parent phenomena. Contemporary theories regarding possible effects on lightning when examined in the light of possible modification effects lead one to predict either a radical increase, a large decrease, or no effect on the frequency of cloud-to-ground discharges. In some storms, the weather modification experiment may shed more light on the parent mechanism since it provides a state in addition to the natural state during which the electrification mechanism can be studied.

#### PRELIMINARY STUDIES, 1958

Our first experiments in randomized seeding were carried out in western Montana in 1958. Three chief objectives of this program were: (1) to test the use of electric field meters for recording lightning discharges in mountainous country, (2) to check methods of visually locating

lightning discharges, and (3) to test seeding techniques and new cloud-seeding equipment. A technique of randomization was used to select certain days for no treatment or treatment from either a network of 30 ground-based generators or from airborne generators.

The frequency of lightning discharges and the electric fields associated with storms were recorded by three synchronized electric field meters. The three recording stations were established along a 14-kilometer line.

The electric field change associated with the discharge to ground of an electrostatic model is given by the equation:

$$\Delta E = \frac{2 \Delta Q H}{4 \pi \epsilon_0 (D^2 + H^2)^{3/2}}$$

where  $\Delta E$  = change in potential gradient (volts/meter)

$\Delta Q$  = total change in charge (coulombs)

$D$  = horizontal distance to strike (kilometers)

$H$  = height of negative charge center (kilometers)

$\epsilon_0$  = permittivity of free space.

The quantity  $2\Delta QH$  is the change in electric moment if the thunderstorm is considered a bipolar electrostatic generator with positive and negative charge centers situated approximately vertically one above another. The electric moment was calculated for cloud-to-ground discharges within the following limitations:

1. The geographical location of a vertical discharge was known.
2. The distance to the charge center  $(D^2 + H^2)^{3/2}$  fell within the domain of acceptable solutions of simultaneous equations for the dipole model (Fitzgerald 1957).
3. The calculated value for  $H$ , the height of the negative charge center, was within the boundaries of the cloud.

The nature of the discharge can be inferred from the polarity of the change in potential gradient. The potential gradient change for a cloud-to-ground discharge is positive at all distances from the discharge. An intracloud discharge has a positive change near the discharge, zero at the reversal distance of about 5 to 7 kilometers, and is negative at all greater distances. Since one field meter is always beyond the reversal distance, we have the following criteria for identifying discharges:

1. A positive change in potential gradient at all field meter sites indicates a cloud-to-ground discharge.

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<sup>2</sup> Measured and calculated values of parameters associated with electrical properties of thunderstorms are given in mks units.

2. A negative change in potential gradient at any site indicates a cloud-to-ground discharge.

In our usage, a cloud-to-ground or ground discharge transfers negative charge to ground. A cloud-to-cloud or cloud discharge could be intracloud, intercloud, cloud-air, or of such a complex nature as to result in a net negative change in potential gradient beyond the field reversal distance.

Continuous electric field records and visual location of discharges were obtained from four untreated storm periods, two ground-seeding periods, and two aerial-seeding periods during the 1958 field season. The normal background freezing nuclei count at cloud base level had been found by the 1957 tracing program to be one nucleus per liter active at  $-20^{\circ}\text{C}$ . We found that the network of ground-based generators could supply about 50 to 300 nuclei per liter at distances of 10 to 15 kilometers from the generator sites. The estimated nuclei concentration at cloud base level produced by the airborne generators was  $10^4$  per liter based on generator output, seeding pattern, updraft velocities, and the physical dimensions of the storm.

The electric field records from the 1958 season provided information on (1) the frequency of lightning discharges, (2) ratio of intracloud to cloud-to-ground discharges, and (3) change of electric moment. These are discussed in detail below.

Frequency of lightning discharges.--The limited number of thunderstorms studied in the 1958 experiment precludes use of statistical methods to test significance of the results. Therefore the data were examined for apparent modification effects that might be verified in subsequent experiments. The grouping of data to examine possible effects of treatment on the frequency of lightning is given in tables 2, 3, and 4.

Table 2.--Average frequency of lightning discharges, 1958

Date	: Number of 5- : minute intervals :	Average number of discharges per 5 minutes		
		Intracloud	: Cloud-to-ground :	Total <sup>1</sup>
<u>Not seeded</u>				
18 July	50	10.5	3.5	15.0
10 Sept.	50	11.4	3.6	15.0
11 Sept.	56	15.4	3.5	19.6
<u>Seeded from ground</u>				
29 July	51	21.0	2.9	24.0
11 Aug.	23	14.5	5.6	21.0

<sup>1</sup> Totals include indeterminate discharges.

In table 2, the average frequency of cloud-to-ground, intracloud, and the total number of discharges per 5-minute period are arranged according to the type of treatment employed. The total number of discharges, which includes all the intracloud and cloud-to-ground discharges, also includes a class of indeterminate discharges which make up about 5 percent of the total. The indeterminate class includes complex discharges and discharges that could not be definitely identified as either intracloud or cloud-to-ground.

Table 3.--Maximum rate of lightning discharges, 1958

Date	: Type of : : discharge :	5 min.	: 10 min. :	15 min.	: 20 min.
<u>Not seeded</u>					
18 July	I.C. <sup>1</sup>	37	67	91	121
	C.G. <sup>2</sup>	15	29	42	55
10 Sept.	I.C.	33	61	89	114
	C.G.	10	15	22	29
11 Sept.	I.C.	51	92	121	164
	C.G.	11	20	27	32
<u>Seeded from ground</u>					
29 July	I.C.	58	111	153	191
	C.G.	10	15	22	28
11 Aug.	I.C.	27	51	66	86
	C.G.	17	30	39	46

<sup>1</sup>Intracloud discharge.<sup>2</sup>Cloud-to-ground discharge.

The treatment may affect the rate at which lightning discharges occur. The maximum rate of discharge occurrence in any 5-, 10-, 15-, or 20-minute period during a recorded storm is shown in table 3.

Table 4 shows the grouping of the total number of intracloud and cloud-to-ground discharges according to the type of treatment each of the five storms received. To compare these storms with a larger sample, we refer to figure 5 which shows total cloud-to-ground discharges per storm recorded by lookouts. The number of discharges seen by lookouts, as previously mentioned, represents only about 50 percent of the actual number recorded by the field meters. After mentally adjusting figure 5 for lookout efficiency, we see that the five recorded storms (table 4) fall near the upper end of the frequency distribution. This means that the five storms recorded by the field meters cannot be considered "average" storms because they produced unusually large numbers of discharges.

Table 4.--Total number of lightning discharges, 1958

Date	:	Intracloud	:	Cloud-to-ground	:	Total <sup>1</sup>
		<u>Number</u>	<u>Percent of total</u>	<u>Number</u>	<u>Percent of total</u>	
			<u>Not seeded</u>			
18 July		527	70	173	23	759
10 Sept.		569	76	181	24	753
11 Sept.		864	78	194	18	1,098
			<u>Seeded from ground</u>			
29 July		1,053	87	147	12	1,218
11 Aug.		335	69	129	27	484

<sup>1</sup> Totals include indeterminate discharges.

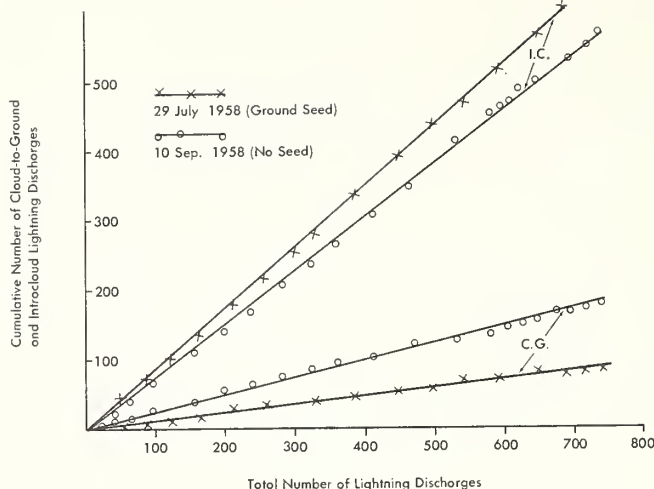


Figure 7.--Regression of cumulative number of intracloud and cloud-to-ground lightning discharges on the total number of discharges for two storm periods.

The lightning frequency values recorded during the five storms lead to the following general conclusion for the cases studied: There were no obvious differences in the frequency of intracloud and cloud-to-ground discharges between nonseeded storms and storms seeded with ground-based generators.

Ratio of intracloud to cloud-to-ground discharges.--Some aspects of thunderstorm electrification theory would lead one to predict a change in the ratio of intracloud to cloud-to-ground discharges even if the total amount of lightning were not changed. The discharge ratios for a storm period can be shown by plotting the cumulative numbers of intracloud and cloud-to-ground discharges against cumulative total discharges for constant time increments during the storm (fig. 7). The points for both intracloud and cloud-to-ground discharges for all storm periods

were joined by a straight line. This linear regression suggested that the ratio of intracloud to cloud-to-ground discharges was generally constant throughout a storm period.

The regression coefficients, which are the slopes of the cumulative curves in figure 7 are listed below for nonseeded storms and for storms seeded by ground-based generators.

<u>Date</u>	<u>Intracloud coefficients</u>	<u>Cloud-to-ground coefficients</u>
	<u>Not seeded</u>	
18 July	0.83	0.08
	.69	.35
18 Aug.	.81	.15
	.77	.15
10 Sept.	.75	.25
11 Sept.	.88	.10
	.72	.24
Average	.77	Average .19
	<u>Seeded from ground</u>	
29 July	.85	.12
11 Aug.	.69	.33
11 Aug.	.78	.15
Average	.77	Average .20

The arithmetic mean of the regression coefficients for cumulative discharge curves indicates there is no difference in the ratio of intracloud to cloud-to-ground discharges between seeded and nonseeded storms and further that the ratio at any interval during a storm period is not altered.

Change of electric moment.--The change in electric moment was calculated from the potential gradient changes and the visual location of the discharges. Calculations from 28 discharges are entered in table 5 along with treatment data. No conclusions about the effectiveness of seeding can be drawn from such a small sample. However, a comparison of the average change in electric moment between nonseeded, ground seeded, and storms seeded from aircraft suggests a reduction in the change in electric moment per discharge in proportion to the quantity of nuclei supplied. The implication is that a cloud seeding program aimed at lightning suppression should attempt to supply at least  $10^4$  nuclei per liter at cloud base level.

Table 5.--Average change in electric moment of lightning discharges

Treatment	: Estimate of nuclei : at cloud base	: Number of : discharges	: Electric : moment	: Standard : deviation
	Number per liter		Coulomb kilometers	
Not seeded	Fewer than 10	8	232	121
Seeded from ground	50-300	17	92	26
Seeded from aircraft <sup>1</sup>	More than 10,000	3	14	6

<sup>1</sup> August 21 and August 22, 1958.

Discussion of the significance of the relation between the change of electric moment and seeding as indicated in table 5 would be rather meaningless in view of the limited number of observations. However, it does seem proper to speculate on what effects these results might have on the design of an experiment.

1. If the observed reduction in electric moment is valid, then the treatment should exceed  $10^4$  nuclei per liter (effective at  $-15^{\circ}$  C.).

2. Reduction in electric moment could mean either that less charge is transferred in the discharge, or that the charge center is lower, or a combination of the two factors. If the charge transferred is less, and if the lightning frequency does not change, then the charging rate within the cloud could be less. It also could be explained by an increase in conductivity between the major charge centers. However, seeding may decrease the intracloud conductivity by increasing the number of ice crystals within the cloud. Future studies should attempt to isolate the variables of the electric moment.

Discussion of aerial seeding cases.--The two storms seeded by airborne generators (table 5), must be considered differently from the examples of ground-based generator seeding. The storm on August 21 had heavy precipitation and a top extending above 39,000 feet, but yielded only three cloud-to-ground discharges and no intracloud discharges. This was the largest storm recorded in or near the test area in 2 years of operation. On August 22 the cloud seeded by airborne generators grew to 30,000 feet, exhibited heavy glaciation, heavy precipitation, and a measured potential gradient in excess of 150 volts per centimeter (measured at the surface).

But this storm produced no lightning discharges. Although the days on which the aerial seeding took place were selected by the established randomization technique, the time and place of seeding on each day were actually arbitrary. There is no assurance that the storms selected for aerial seeding would have developed into large thunderstorms. However, large storms did occur near the test area on both days.

For planning the evaluation of lightning suppression experiments, the following possibilities should be noted:

1. Several researchers have reported that the larger or higher a thunderstorm system, the more intense will be the lightning activity. This has been confirmed for all thunderstorms studied except for the two storms reported above. This anomaly could mean that such storms occur naturally or that seeding with a high concentration of nuclei substantially decreases lightning activity. If these storms occur naturally, the evaluation technique must allow for such an anomalous storm that shows all the physical characteristics of a very large thunderstorm but exhibits little or no lightning activity.

2. If lightning frequency for thunderstorm periods is used as a basis to measure the effectiveness of lightning suppression techniques, a paradox is immediately present in the evaluation. A 100-percent effective system of lightning suppression would exclude all treated cases from the classification as thunderstorms since, by definition, a thunderstorm requires that lightning occur. The seeded cloud described for August 22 could not be considered a thunderstorm since lightning was not seen nor thunder heard. However, the field meters recorded intense electrical activity.

The preliminary studies in 1958 permitted a close look at the problems associated with field experiments in lightning storm modification, and provided valuable information for a realistic design of subsequent experiments.

## 1959 STUDIES

Results of the 1958 field studies indicated need for a long-range program to study thunderstorms under treated and untreated conditions. The following elements were believed to be of primary importance:

1. Development of an adequate measuring system for recording lightning parameters.
2. Establishment of this recording system in a suitable area.
3. Development of an airborne silver iodide smoke generator capable of supplying large numbers of nuclei.

A 3-year observational program using a synchronized network of five surface-mounted electric field meters was designed to study the following:

1. The frequency and distribution of lightning discharges during natural storms.
2. The quantity of charge carried by cloud-to-ground discharges.
3. The height of negative charge centers.
4. The effect of silver iodide seeding from aircraft on some of the electrical and physical characteristics of lightning storms.

In addition to the above, the Skyfire lookout network was expanded from 22 to 38 stations. This expansion provided supplementary information on the regionwide occurrence of lightning storms, cloud-to-ground discharges, and surface weather conditions.

Because of a limited operational budget, only a portion of this program was planned for completion during the 1959 field season. Also the summer of 1959 had a record low number of thunderstorm days; the frequency of storms was only about 40 percent of normal. As a result, the data collected were insufficient to permit any statistical studies of lightning storm features.

An airborne silver iodide generator was developed to produce about  $10^{15}$  nuclei per second effective at  $-20^{\circ}\text{C}$ . This airborne generator and a similar ground-based unit are described fully in Section VII.

A new study area (fig. 8), established on the Deerlodge National Forest near Philipsburg, Montana, was selected because:

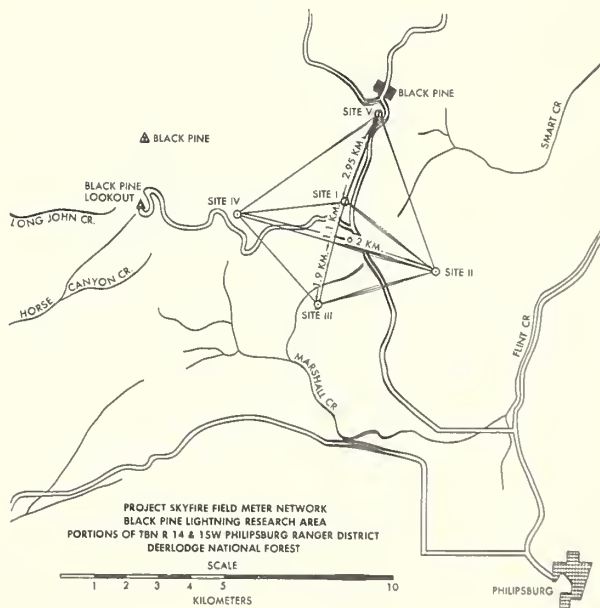
1. It had a relatively high frequency of lightning occurrence.
2. It had an adequate road system.
3. It was close enough to Missoula for aircraft and service operations from existing facilities.

The electric field meter and lightning observing sites established within the study area (fig. 9) were located in a prescribed geometrical pattern. The instrumentation at each site included a recording electric field meter, a means for visually locating lightning discharges, and surface weather observing equipment. At one station, the instrumentation included a mobile radar unit, time-lapse and full-sky cameras, and upper wind measuring equipment. The field meters at each site were connected through a land-line system to a central station to insure synchronization of recordings.



Figure 8.--Project Skyfire research areas, 1957-60.

Figure 9.--Project Skyfire study area near Philipsburg, Montana, 1959-60, showing field meter network.



On November 15, 1959, additional funds to plan and carry out a program of research on the effects of cloud seeding on lightning storms became available through a cooperative program with National Science Foundation.

## V. DESIGN OF EXPERIMENTS FOR 1960-61

The weather modification program for 1960-61 was planned to last  $2\frac{1}{2}$  years and to include two field seasons. This period may not have enough lightning storms to give data for statistical conclusions. Plans have been made to extend the study until valid conclusions can be reached.

The research program has the following objectives:

1. To obtain information on the frequency, type, and electrical characteristics of lightning discharges and to evaluate this information in relation to theories about thunderstorm development and electrification.
2. To determine the effects on the frequency and electrical characteristics of lightning discharges when clouds are heavily seeded with silver iodide and to evaluate the results in relation to theories on lightning.

### STATISTICAL DESIGN

The basis of the cloud-seeding experiment is the comparison of electrical and physical factors in lightning storms on pairs of treated and untreated days. The pairing was adopted to insure an equal number of treated and untreated days. Selection of an operational day in an unbiased manner is accomplished by using, as a basis of declaration, a U.S. Weather Bureau forecast that thunderstorms will occur in the test area. The forecast, by 1100 m.s.t., must call for a thunderstorm to occur in the test area between the hours of 1300 and 1900 m.s.t. A table of random numbers then is used to determine whether the day will be one for treatment or control. When one day has been prescribed, the next operational day, with any number of nonoperational days intervening, completes the pair by receiving the opposite treatment. Identical observations are taken on both treated and untreated days.

On operational days when seeding is done, two aircraft on alternate shifts dispense silver iodide upwind of the test area. The aircraft may be forced from the area for short periods of time during the passage of very active storms. To strive for continuity of treatment during these periods, three ground-based generators also release silver iodide into the test area.

The statistical analysis is designed to compare the following variables on paired days:

1. Frequency of cloud-to-ground and intracloud discharges.
2. Total number of lightning discharges.
- \*3. Electric moment of cloud-to-ground discharges.
- \*4. Vertical height of negative charge centers.
5. Height of initial radar echoes.

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\*Values computed for a monopole discharge from an electrical model of a thunderstorm.

6. Rate of vertical growth of radar echoes.
7. Maximum height of visible cloud tops.
8. Rate of growth of visible cloud tops.

The analysis should give a statistical answer to the following list of questions. In each case the alternate hypothesis is stated. The null hypothesis is the obvious negative statement of the question:

1. Does cloud seeding alter the occurrence of lightning discharges?

Hypothesis: Cloud seeding changes the number of cloud-to-ground discharges.

Hypothesis: Seeding changes the number of intracloud discharges.

Hypothesis: Seeding changes the total number of discharges.

Hypothesis: Seeding changes the ratio of cloud-to-ground to intracloud discharges.

2. Does cloud seeding alter the electrical properties of discharges?

Hypothesis: Seeding changes the electric moment.

Hypothesis: Seeding lowers the vertical height of the charge centers.

3. Does seeding alter the physical characteristics of the cloud?

Hypothesis: Seeding lowers the height of the maximum height of radar echo.

Hypothesis: Seeding lowers the height of the initial radar echo.

Hypothesis: Seeding changes the rate of growth of radar echo.

Hypothesis: Seeding changes the maximum height of visible cloud top.

Hypothesis: Seeding changes the rate of growth of clouds.

The following two considerations were declared in a study plan prior to the 1960 field season:

1. Simple nonparametric procedures, usually signed rank tests, will be used.

2. A 95-percent level of significance will be used; however, results will be presented with the level of significance at which the null hypotheses could be rejected.

Because of the large variances and the limited number of pairs that would be available during the two seasons, the project may fail to detect, as significant, differences that actually exist. This motivates the inclusion of the level of significance at which the null hypotheses could be rejected and allows an objective combination of the results of this experiment with those from other experiments. Suppose, for instance, that the results of this study show an apparent tendency for the seeded member of a pair to have a level of initial precipitation formation lower than the unseeded member of a pair, but that this tendency is not statistically significant. It may well happen that other weather modification experiments will also test the hypothesis that cloud seeding lowers the level of precipitation formation. Suppose, for concreteness, that each study separately could have rejected the hypothesis of no change in the level of precipitation formation at the 95-percent level of significance. It would seem that the two "almost significant" results might together significantly indicate lowering of the formation level. This is, in fact, true. Objective techniques, originated by R. A. Fisher (1936) and developed by others,

allow the combining of the results of two different experiments. The statistic used is the level at which the null hypothesis could have been rejected. (For the combination of results it is not necessary that the second experiment be an exact replication of the first; it is sufficient that the experiment be testing the same null hypothesis.)

As pointed out by the report of the Skyline Conference (National Academy of Sciences 1959), weather modification experiments offer an opportunity to supplement present descriptions of storms. Descriptive observations made by project personnel may make possible the use of more precise statistical techniques. For instance, nonstatistical examination of storms may make plausible the assumption of a particular frequency distribution for lightning occurrence. This distribution could then be used in the statistical tests. Of course, only data gathered after the assumption of a particular distribution can be analyzed by the revised technique. The possibility of applying techniques of extreme value statistics will also be considered.

## SOLUTIONS OF CLOUD-TO-GROUND LIGHTNING DISCHARGES

In this section we examine the relation between electric field recorded at the surface and changes in the thunderstorm caused by cloud-to-ground lightning. The following discussion is based on a point-charge model of a thunderstorm.

It is generally accepted that the thunderstorm exhibits a bipolar charge distribution with the positive charge center located higher in the cloud than the negative center. Further, it is assumed that the charges can be treated as point charges if the distance to a point of observation on the ground is large. If we consider only the negative charge center of  $Q$  coulombs located  $H$  meters above any infinite conducting plane and  $D$  meters horizontally from the point of observation, the vertical component of the electric field,  $E$  in volts per meter, is given by the following equation:

$$E_z = \frac{2QH}{4\pi\epsilon_0(D^2 + H^2)^{3/2}} \quad (1)$$

where  $\epsilon_0 = 8.85 \times 10^{-12}$  farads per meter, the permittivity of free space.

When the charge is lowered to earth by a cloud-to-ground lightning discharge, the change in field is given by:

$$\Delta E_z = \frac{2\Delta QH}{\epsilon(D^2 + H^2)^{3/2}} \quad (2)$$

where  $2\Delta QH$  is the change in electric moment of the discharge and  $\epsilon = 4\pi\epsilon_0$ .

A set of four equations is required to solve for the variables  $\Delta Q$ ,  $H$ , and  $D$  (where  $D$  is given in terms of  $X$  and  $Y$  from the center of a coordinate system). This requires simultaneous recordings of  $\Delta E$  at four locations.

If the location of a discharge at the ground surface is known, the height  $H$  can be calculated from the following equations:

$$\frac{\Delta E_i}{\Delta E_j} = \left[ \frac{D_j^2 + H^2}{D_i^2 + H^2} \right]^{3/2} \quad (3)$$

or solving for  $H^2$

$$H^2 = \frac{\left[ \frac{\Delta E_i}{\Delta E_j} \right]^{2/3} D_i^2 - D_j^2}{1 - \left[ \frac{\Delta E_i}{\Delta E_j} \right]^{2/3}} . \quad (4)$$

The quantity  $\Delta Q$  can then be calculated from equation (2).

In our research area in western Montana, four electric field meters were located in a geometric pattern as shown in figure 9. A fifth field meter site was added later to help identify the electrical discharges. The following solutions to equation (2), based on the geometry of the field meter network, follows closely the analysis presented by Fitzgerald (1957).

The line through meter sites II and IV (fig. 9) establishes the X axis, and the line through sites I and III, which is nearly perpendicular to the X axis, is taken as the Y axis.

The distances from the center of the coordinate system to the location of sites I, II, III, and IV are  $A_1$ ,  $B_1$ ,  $C_1$ , and  $D_1$ , respectively. In this network  $B_1 = D_1$  and  $C_1 = \emptyset A_1$ .

The following four equations involving the field changes at each of the four sites from a discharge of  $\Delta Q$  at slant distance  $R$  can now be written in terms of this coordinate system:

$$R^2 - 2A_1Y + A_1^2 = \left[ \frac{2 \Delta QH}{\epsilon} \right]^{2/3} \Delta E_1^{-2/3} \quad (5)$$

$$R^2 - 2B_1X + B_1^2 = \left[ \frac{2 \Delta QH}{\epsilon} \right]^{2/3} \Delta E_2^{-2/3} \quad (6)$$

$$R^2 + 2C_1Y + C_1^2 = \left[ \frac{2 \Delta QH}{\epsilon} \right]^{2/3} \Delta E_3^{-2/3} \quad (7)$$

$$R^2 + 2D_1X + D_1^2 = \left[ \frac{2 \Delta QH}{\epsilon} \right]^{2/3} \Delta E_4^{-2/3} \quad (8)$$

where  $R^2 = X^2 + Y^2 + H^2$  and  $\Delta E_1$ ,  $\Delta E_2$ ,  $\Delta E_3$ , and  $\Delta E_4$  are the field changes at sites I through IV.

Eliminating  $X$  and  $Y$  by substituting for  $C$  and  $D$ , multiplying equation (5) by  $\emptyset$ , and adding equations (5) and (7), and equations (6) and (8), we have the following two equations:

$$R^2 + \emptyset A_1^2 = \frac{\left[ \frac{2 \Delta Q H}{\epsilon} \right]^{2/3} (\emptyset \Delta E_1^{-2/3} + \Delta E_3^{-2/3})}{(1 + \emptyset)} \quad (9)$$

$$R^2 + B_1^2 = \frac{\left[ \frac{2 \Delta Q H}{\epsilon} \right]^{2/3} (\Delta E_2^{-2/3} + \Delta E_4^{-2/3})}{2} . \quad (10)$$

Eliminating R by subtracting equation (10) from equation (9), we have

$$\left[ \frac{2 \Delta Q H}{\epsilon} \right]^{2/3} = \frac{2 (1 + \emptyset) (\emptyset A_1^2 - B_1^2)}{2 \alpha^2 - (1 + \emptyset) \beta^2} \quad (11)$$

where

$$\alpha^2 = \emptyset \Delta E_1^{-2/3} + \Delta E_3^{-2/3}$$

$$\beta^2 = \Delta E_2^{-2/3} + \Delta E_4^{-2/3} .$$

We next solve for  $R^2$  by adding equations (9) and (10) and substituting for  $\left[ \frac{2 \Delta Q H}{\epsilon} \right]^{2/3}$  from (11).

$$R^2 = \left[ \frac{\emptyset A_1^2 - B_1^2}{2 \alpha^2 - (1 + \emptyset) \beta^2} \right] \left[ \frac{2 \alpha^2 + (1 + \emptyset) \beta^2}{2} \right] - \frac{(\emptyset A_1^2 + B_1^2)}{2} . \quad (12)$$

Following the same procedure, we have the following equations for X, Y, H, and  $\Delta Q$ :

$$X = \frac{(1 + \emptyset) (\emptyset A_1^2 - B_1^2) (E_4^{-2/3} - E_2^{-2/3})}{2 B_1 [2 \alpha^2 - (1 + \emptyset) \beta^2]} \quad (13)$$

$$Y = \frac{(\emptyset A_1^2 - B_1^2) (E_3^{-2/3} - E_1^{-2/3})}{A_1 [2 \alpha^2 - (1 + \emptyset) \beta^2]} - \frac{(\emptyset - 1) A_1}{2} . \quad (14)$$

$$H = (R^2 - X^2 - Y^2)^{1/2} \quad (15)$$

$$\Delta Q = \frac{\epsilon}{2H} \left[ \frac{2 (1 + \emptyset) (\emptyset A_1^2 - B_1^2)}{2 \alpha^2 - (1 + \emptyset) \beta^2} \right]^{3/2} . \quad (16)$$

A real solution is governed by the condition that  $R^2 > 0$ . Applying this condition to equation (12), we have

$$\left[ \frac{\emptyset A_1^2 - B_1^2}{2 \alpha^2 - (1 + \emptyset) \beta^2} \right] 2 \alpha^2 + (1 + \emptyset) \beta^2 > \emptyset A_1^2 + B_1^2 . \quad (17)$$

In this network

$$A_1 = 1.07 \times 10^9 \text{ meters}$$

$$B_1 = 3.02 \times 10^9 \text{ meters}$$

$$\emptyset = 1.8 .$$

Substituting for  $A_1$ ,  $B_1$ , and  $\emptyset$  in equation (17), we have

$$\frac{3.75 (1.40 \beta^2 + \alpha^2)}{140 \beta^2 - \alpha^2} > 5.80 . \quad (18)$$

If we let

$$\frac{\beta^2}{\alpha^2} = \tau$$

then equation (18) becomes

$$\frac{3.75 (1.40 \tau + 1)}{1.40 \tau - 1} > 5.80 .$$

Therefore, the range of  $\tau$  for real solutions is

$$0.714 \leq \tau \leq 3.33 . \quad (19)$$

Equation (19) is used to determine if we have a real solution to the above equations for a given set of field changes.

## VI. STATISTICAL REPORT--1960 FIELD SEASON

The first field season for the experiment described in Section V was from July 1 through September 12, 1960. Measurements taken during 16 operational days provided eight pairs of treated and untreated days for statistical analysis. The number of pairs is lower than would be expected for an average season. The number and types of recorded discharges for operational days in 1960 are summarized in table 6.

Description of the statistical analysis for these experiments with reference to testing procedures was prepared before the experiments were conducted. Simple nonparametric procedures--usually signed rank tests--were to be used. Since the first season's data are now available, these procedures should be reviewed for possible modification in future experiments. It should be emphasized that we could not reasonably expect statistically significant results from the first year's work. While results from the first year's work are given here, this report should be regarded as a first review of the problem and not as a statement of final results of the experiment.

Table 6.--Number and types of discharges recorded, 1960

Date	: Cloud-to-ground :	Intracloud	: Indeterminate :	Total
<u>Untreated days</u>				
13 July	106	52	4	162
20 July	13	68	4	85
28 July	0	0	0	0
3 Aug.	117	212	11	340
22 Aug.	0	0	0	0
25 Aug.	0	0	0	0
2 Sept.	0	0	0	0
4 Sept.	0	0	0	0
Total	236	332	19	587
<u>Treated days</u>				
14 July	3	8	1	12
22 July	12	110	0	122
27 July	0	0	0	0
10 Aug.	0	0	0	0
15 Aug.	0	0	0	0
26 Aug.	0	0	0	0
31 Aug.	6	45	3	54
3 Sept.	0	0	0	0
Total	21	163	4	188

## CHOICE OF TESTS

We consider next the choice of appropriate statistical techniques, their application to Project Skyfire data, and their implications for further study.

For comparing two treatments using unpaired data, the following five tests are available:

1. Run test (Dixon and Massey 1957). This test is sensitive to detecting differences in shape (including differences in medians) of two distributions.
2. Median test (Dixon and Massey 1957). This test is sensitive to detecting differences between two medians.
3. Rank-sum test (Dixon and Massey 1957). This test is sensitive in detecting differences characterized by one cumulative distribution function being always above the other.
4. Permutation test (Scheffé 1959). This test is sensitive in detecting a difference characterized by one cumulative distribution function being a translation of the other.
5. Standard t-test. This test is sensitive in detecting differences described in (4) when a distribution is normal (this, of course, is a parametric test).

The above tests are listed in order of decreasing applicability and increasing power. Usually one should choose a test as far down the list as possible; one must sacrifice power (probability of detecting real differences) in order to gain in area of applicability in any specific application.

For comparing treatments using paired experimental units the following tests are available:

1. Sign test (Dixon and Massey 1957). This test is similar to the median test for unpaired data (No. 2 in the list above).
2. Signed rank test (Dixon and Massey 1957). This test is similar to the Mann-Whitney test for unpaired data (No. 3 in the list above).
3. Permutation test (Scheffé 1959). This is similar to the permutation test for unpaired data.
4. Standard t-test.

As in using tests for unpaired data, one should choose a test as far down the list as possible.

When we examine these tests in light of the discharge data provided by the 1960 field experiments (table 6), we see the discharge frequency is not normally distributed. Therefore, test 4, the t-test, is probably inappropriate. We further note that most days have zero discharges. It seems likely that cloud seeding would not completely eliminate this zero class; therefore, test 3 also is inappropriate for the frequency function. Thus, among the tests in the standard repertoire, the signed rank test seems most appropriate for these data.

Usually experimental units are paired to control a source of variability. To make such pairing profitable, considerable variability must be removed; for the pairing effectively halves the number of experimental units. In the experiments described here, the units were paired primarily to insure an equal number of treated and untreated days. Since the number of experimental units was not known in advance, they could not be divided into two equal groups by a random selection. One would like to regain the "lost degrees of freedom." Two appealing possibilities are:

1. To ignore the fact that experimental units were paired, and analyze the data accordingly. However, one must--perhaps unfortunately--play statistics according to the statistician's rules. One fundamental principle is: ". . . whenever a source of uncontrolled variation is eliminated from the error in the design of the experiment, it must also be eliminated in the analysis. . . ." (Cox 1958, p. 76).

2. To eliminate the source of error from the analysis (in this case the difference between pairs), and test statistically whether there is in fact a difference between pairs. If this test shows no significant difference, we could then claim we have experimental evidence that pairing may be ignored. This test is frequently used. However, Scheffé (1959, p. 126) says, "Not very much is known about the operating characteristics of these procedures, and it seems best to try to avoid such pooling. . . ." It appears best to treat these data as paired experimental units. We also conclude that the signed rank test can most logically be applied to these data.

The signed rank test eliminates ties from the data. This seems to be a dangerous practice since ties would indicate no treatment difference. The theoretical justification for eliminating ties (i.e., that ties occur with probability zero in the continuous model for which the distribution of the statistics has been found) does not apply to the discrete data at hand. The only ties found in these data came from pairs of days on which no lightning occurred. Such ties would not have occurred if there had been a perfect way to forecast occurrence of thunderstorms. Elimination of these zero ties does not reduce the possibility of detecting no difference due to treatment. In the untreated case, a zero means lightning did not occur. A zero in the treated case could have the same meaning or could mean that treatment was 100 percent effective in reducing lightning. The latter possibility appears unlikely, but must be considered.

## STATISTICAL ANALYSIS OF 1960 LIGHTNING DATA

Lightning data from eight pairs of days during 1960 were analyzed by the statistical tests described in the previous section.

The following variables were examined:

1. Frequency of cloud-to-ground, intracloud, and total lightning events.
2. Ratios of cloud-to-ground to intracloud events.
3. Differences in electric moment.

Comparison of numbers of lightning events.--Analysis of the 1960 data by signed rank tests shows no significant difference between treated and untreated experimental units in total number of lightning events, total number of cloud-to-ground events, or total number of intracloud events. The probability of the distribution of lightning events listed in table 6 occurring by chance was greater than 0.25 in every case for a two-sided test. It should be noted that

these data are not independent. Except for a small number of indeterminate events, total events are the sum of cloud-to-ground and intracloud events. An anomalous storm might be responsible for erratic behavior in several of the test statistics used and thus give rise to several simultaneous incorrect inferences.

Comparison of ratios of cloud-to-ground to intracloud events.--One can compare ratios only in pairs for which discharges occurred on both days. Since the 1960 season had only two such pairs, there was no hope of finding statistical significance by using the signed rank test.

Differences in electrical properties.--Values of electric moment and height of charge center were obtained on two untreated days and one treated day. Mann-Whitney tests (Tate and Clelland 1957) were used since data were not available for paired treatment units. These tests indicated no difference in electric moment ( $P=0.68$ ) or in vertical height of charge center ( $P=0.50$ ) between treated and untreated days. The assumptions of the Mann-Whitney test are probably not fulfilled, thus we must wait for sufficient pairs to make conclusions using signed rank tests.

## GENERAL COMMENTS

If one keeps in mind the seductive nature of unjustified statistical procedures, total events on all days (operational and nonoperational) when lightning events occurred after 1300 m.s.t. can be compared, using the Rank-sum test. The probability is 0.15 that such a difference as occurred could have occurred by chance. This puts the very best face on things. If one includes all days when observations were made, even days with no events, the probability is increased to 0.46; so that chance alone is a good explanation.

The present experimental design needs many more observations before statistically significant conclusions can be obtained. It now seems extremely unlikely that only one or two more summers of observations will produce statistically significant results.

Increased knowledge of thunderstorm activity could lead to improved experimental technique, and to a more completely determined statistical model. Also, this knowledge could lead to a more restrictive definition of an experimental unit, rendering statistical technique more powerful. For example, variability could probably be reduced by eliminating days on which no lightning would have occurred in the absence of seeding. Since it is impossible to identify such days, they must be left in the analysis and consequently, to avoid bias, untreated days when no lightning occurred must also be left in the analysis.

Another possibility for increasing precision is the use of analysis of covariance. For this to be effective, appropriate control variables must be chosen. This choice seems to require greater knowledge of the nature of thunderstorms. With only a small number of experimental units one dares not choose control variables that "seem" reasonable. Each control variable uses up a degree of freedom and not many of these are available.

## VII. INSTRUMENTS AND EQUIPMENT

### SILVER IODIDE SMOKE GENERATORS

Development of suitable equipment for cloud seeding in mountainous and forested areas has been a major problem of Project Skyfire. Early work with calibration and evaluation of existing equipment led to development of a highly efficient ground-based generator. Full details

of the calibration and equipment development are available in other reports (Fuquay 1960; Fuquay and Wells 1957). Thirty of the new ground-based generators were used during the 1957 and 1958 field seasons. The equipment operated satisfactorily.

Development of airborne generators was begun in 1958. A suitable generator had to have the following design and safety features (Fuquay 1960):

1. A self-contained unit that could readily be mounted on a contract aircraft.
2. A nonpressurized solution source entirely independent of the pilot's compartment.
3. A simple fail-safe control system that could be adapted to any aircraft to protect the plane and forested areas from danger of fire.
4. Operation at high efficiency in the speed range of 80-140 m.p.h.
5. Operation without major interference with the flight characteristics of the aircraft.

Designs for a solution injection system and a burning chamber were developed concurrently because these two parts are interdependent. The solution system was to be nonpressurized. We first tried to use a conventional venturi nozzle to deliver about 3 gallons of solution per hour to a burning chamber. When the venturi was located in the inflow airstream, large deposits of AgI-NaI accumulated on the walls of the intake because of the frictional transfer of momentum. As the size of the channel was increased, the volume of air became too large to maintain a stable flame in any reasonably sized burning chamber. Throttling the intake air resulted in inefficient burning of the solution and a consequent low output from the generator. Attempts to locate the injection system in the high temperatures of the burning chamber resulted in serious clogging of the nozzles.

Evidently, two features were necessary for proper operation of an airborne generator with the required characteristics. First, the large flow of solution must be injected directly into an open flame chamber. Second, the large volume of air required to burn 3 gallons per hour efficiently must be contained in a small volume in order to attain the required  $1200^{\circ}\text{C}$ . temperature. A new design was developed to meet these needs.

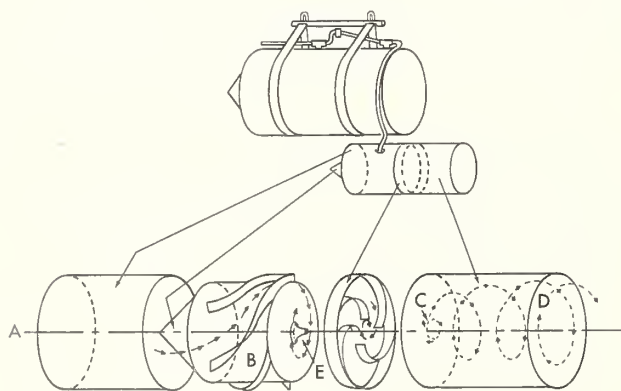


Figure 10.--Project Skyfire experimental airborne silver iodide smoke generator.

The new generator consists of three main parts: a solution reservoir of about 10-gallon capacity, an intake swirl chamber, and a burning chamber (fig. 10). Air rammed into the generator at A by the motion of the airplane is deflected into a high-velocity rotating airstream by the deflecting vanes B. The rotating air passes through opening C into flame chamber D. The centrifugal effect of the air rotating at point C results in a pressure reduction of about 60 mm. of mercury at nozzle E. This pressure reduction is sufficient to start the flow of solution to nozzle E, where it is nebulized by the airstream and carried into the burning chamber D.

Figure 11.--Solution control system for experimental airborne silver iodide smoke generator.

Controlling the AgI-NaI-acetone solution flow has always been a problem in generators because of clogging and corrosive effects of the solution. In this generator the flow is controlled without the solution making contact with any control valves. The solution flow, shown in figure 11, is controlled by a single solenoid valve at H. When the generator is airborne, ram pressure at F forces air through the solenoid valve H and through the nozzle to the burner. The pressure is equal

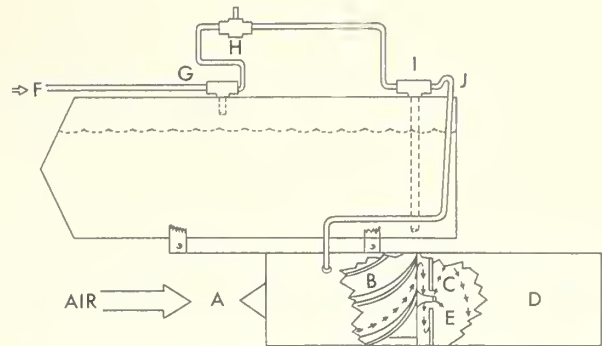


Figure 12.--Airborne silver iodide generator being mounted on Cessna-180 aircraft.

at G and I and no solution is moved from the reservoir. When the solenoid is energized, valve H is closed, and ram pressure is present on the top of the solution. The pressure reduction at the nozzle starts the flow of solution through tube J to the burner. When the solenoid is deenergized, the flow of solution is stopped, and ram pressure purges the lines of any remaining solution.

In the event of a malfunction or aircraft trouble, the generator can be jettisoned from the aircraft by triggering the bomb rack release switch. If the generator is operating at the time of release, the solenoid power is interrupted through a pull-out plug and the flame is immediately extinguished. Figures 12 and 13 show the generators mounted on a Cessna-180 aircraft.

Figure 13.--Closeup view of airborne generator.

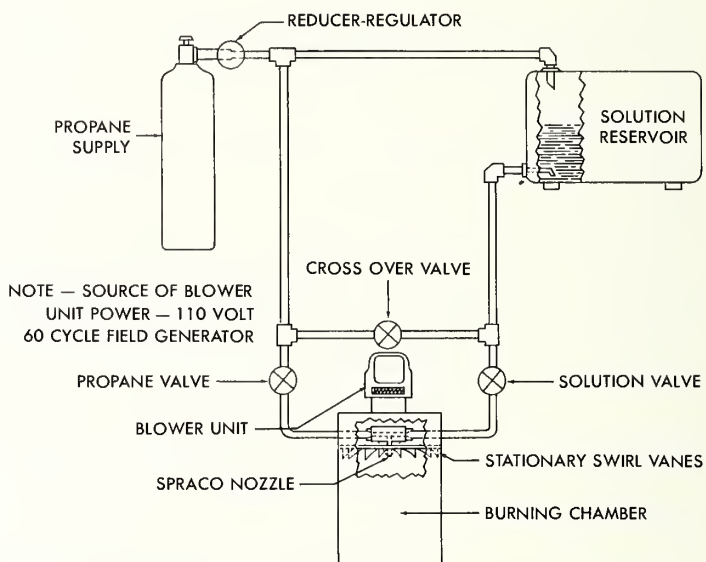
Rough field calibrations of the airborne generator, using the portable coldbox and wind tunnel technique (Fuquay 1960), indicates a production rate of about  $10^{15}$  nuclei per second effective at  $-20^{\circ}$  C. Consumption rate was about 3 gallons per hour of 10 percent silver iodide-sodium iodide-acetone solution.



Successful operation of the new airborne generator led to development of a ground-based unit having similar characteristics. Construction of this generator was greatly simplified by using a commercially available spark arrestor as the swirl and burning chambers. However, this design requires a slightly pressurized solution tank.

The ground-based generator consists of a number 5C-20A Gill Spark Arrestor with a Spraco nozzle mounted at one end of the burning chamber, a barrel to hold the solution, a high-capacity blower, and assorted tubes and valves (fig. 14). A Skil blower (type 26) supplies a forced draft through the swirl chamber. Propane gas pressure forces the solution through the Spraco nozzle and into the burning chamber. The valve arrangement permits purging the line and nozzle of solution by diverting the gas flow through the supply line when the generator is shut down.

Figure 14.--Schematic diagram of ground-based silver iodide smoke generator.



AgI GROUND-BASED GENERATOR

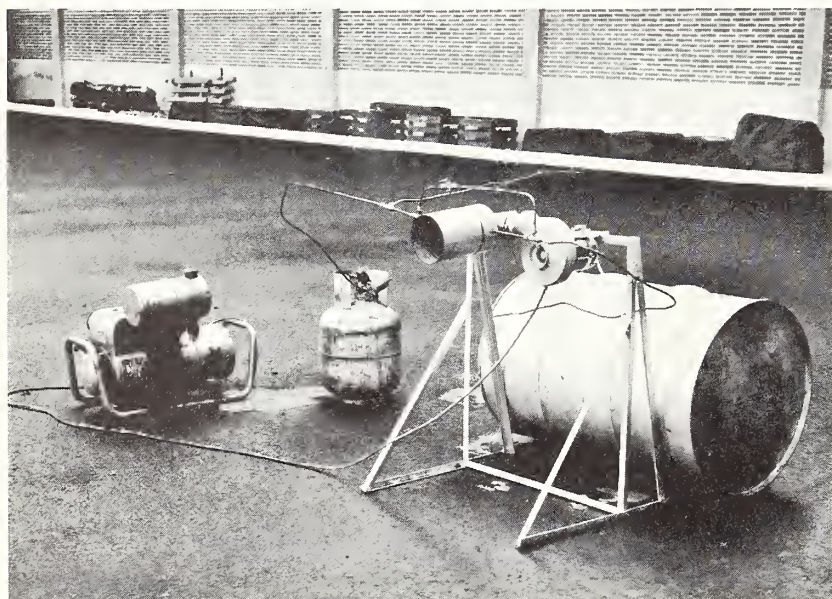


Figure 15.--Ground-based silver iodide smoke generator.

## ELECTRIC FIELD METERS

The vertical component of the electric field associated with thunderstorms is measured with alternating current type field meters developed by Dr. Ross Gunn (1954). The meter operates on the principle that a conductor exposed in an electric field and then earthed will pick up and release a charge in proportion to the electric field.

An inductor, mounted on the shaft of a small motor, is rotated at a constant speed in a plane parallel to the vertical electric field. The inductor emerges from a shield, such that each end of the inductor successively becomes exposed to the electric field and returns to within the shield. A charge is induced on the highly insulated inductor each time it is exposed to the field. The resulting alternating potential is amplified, rectified, and applied to a d.c. recorder. To eliminate the difficulties associated with a commutator, the circuit is made phase-sensitive by unique application of the principles of a locked-in amplifier. An a.c. generator, mechanically synchronized with the inductor, provides the a.c. voltage necessary to phase or lock in the signal from the rotating inductor.

The inductor portion of the meter is located in the center of a 5-foot-square reference plane (fig. 16). To calibrate the meter, a second screen is suspended on insulators at a fixed distance above the reference plane. The meter zero reading is adjusted by grounding the second screen. The meter scales are determined by adjusting appropriate attenuators when known voltages are applied between the screens.



Figure 16.--Electric field meter ground reference planes, near Philipsburg, Montana.

## CENTRAL TIMING SYSTEM

The land line connecting all electric field recording sites to a central location is used to synchronize the recordings. A timing unit with a synchronous motor drive was modified to produce a low-voltage pulse at each 30-second or 1-minute interval. In addition, each 5- or 10-minute pulse was coded for easy identification. A synchronous dial, with reset movement, totalizes the time from the beginning of operations.

The interval pulses generated by the timing mechanism are introduced directly into the land line. At the receiving end, the time pulses actuate a low-power relay switch. This relay energizes the chronographic pen on the left edge of the electric field recorder chart. Thus, chronographic synchronizing pulses are recorded simultaneously on each field meter chart.

## LIGHTNING SPOTTING

U.S. Forest Service fire lookouts have been locating the strike points of cloud-to-ground lightning discharges for many years. The strike point is located because the lookout must keep this spot under surveillance for several days since many lightning fires do not flare up until several days after the lightning discharges occur. A standard fire-finder is used to locate the strike point. Accurate azimuths can be obtained by using the fire-finder, but each sighting takes up to a half minute. As a result, the fire lookout can locate only a portion of the cloud-to-ground discharges in his immediate area. The fire-finder is not a suitable tool for locating all cloud-to-ground discharges occurring in a given area.

Attempts have been made to record positions of lightning discharges by using cloud theodolites and alidades. These instruments are smaller and easier to handle than the fire-finder, but the spotting efficiency is still poor. The primary problem is that the operator can survey only a small portion of the horizon while discharges may be occurring in all quadrants. An instrument that can view a full 360° of the horizon is necessary.

The schematic diagram of a lightning spotter is shown in figure 17. This spotter consists of an inverted parabolic mirror, a lens system, and a plotting board. The image of a lightning discharge appearing on the parabolic mirror is focused on the plotting board in a darkened room by a 4-inch diameter, 24-inch focal length lens. The direction of the lightning discharge is read from a circular azimuth ring on the plotting board and recorded on the field meter record.

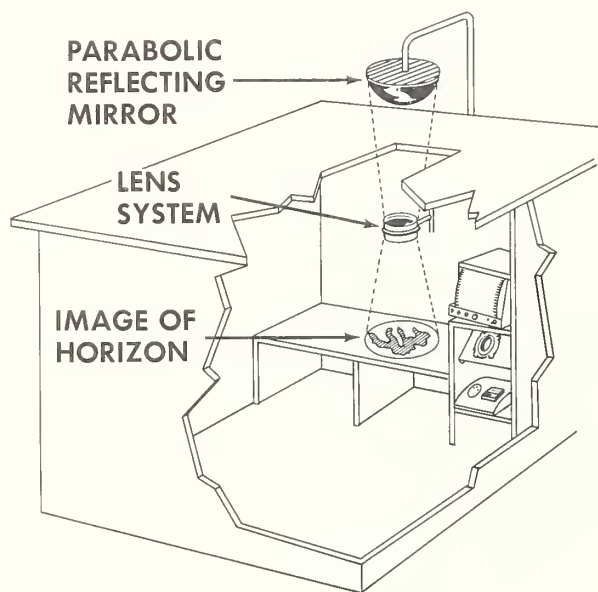


Figure 17.--Lightning spotting system installed in an 8-foot-square observation shelter.

## RADAR

In the spring of 1960, two military surplus SO-12 M/N radar units were obtained for use on the project. The truck-mounted radar units, with attached gasoline power units, proved very satisfactory for field activities. Both radars were modified to transmit in the 9300-9500 megacycle weather band by installation of type 725A magnetrons.

One radar set (fig. 18) gave a standard PPI presentation of the location and movement of precipitation cells. It detected well-developed thunderstorms at the maximum range of 100 nautical miles.

The second radar set (fig. 19) was extensively modified to make range-height measurements of precipitation cells within the test area. The major changes in the set were:

1. Modification of the antenna system to permit vertical scan from horizon to horizon.
2. Construction of a mount so the radar could be rotated through a full circle.

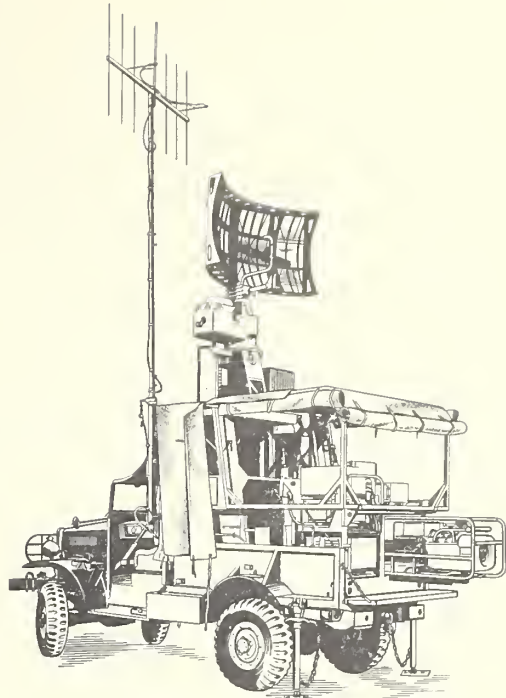


Figure 18.--Search radar unit used to record location and movement of precipitation cells in study area.

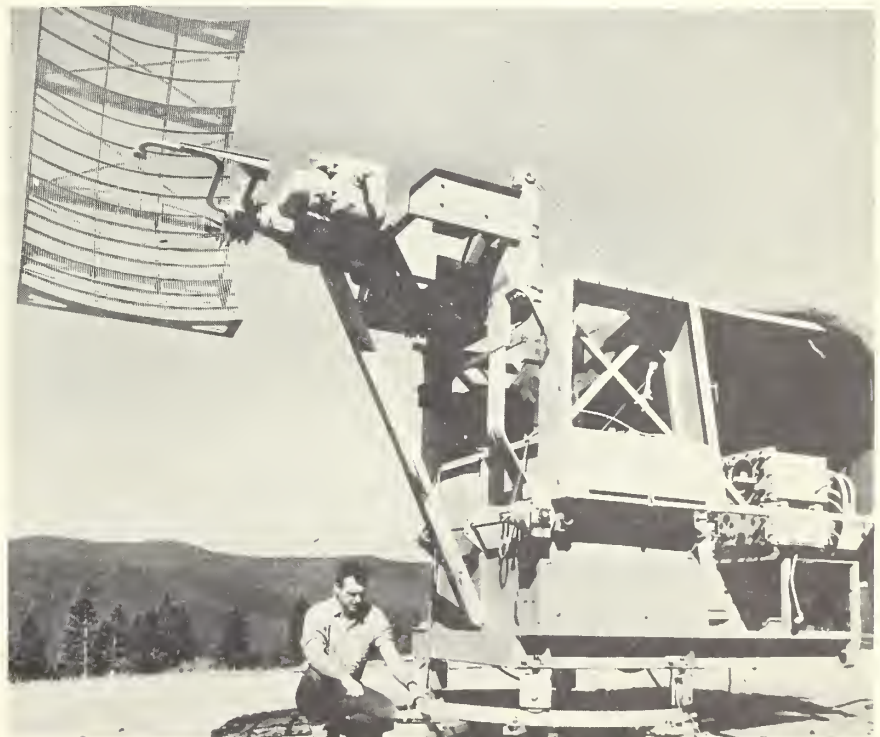


Figure 19.--Modified search radar used to make range-height measurements on precipitation cells within the study area.

3. Changes in the indicator unit for best presentation of range-height information.
4. Adaptation of a remote indicator to the radar.

The output of both radars was connected through a selector switch to a remote repeater scope (type VD-2). An automatic camera connected to the repeater recorded the radar information. In normal practice, the PPI picture was recorded for 2 minutes and the range-height image was recorded for the remainder of a 15-minute interval.

### PRECIPITATION AND HAIL GAGES

The total amount of precipitation on operational days was measured at five locations in the test area. A Bendix-Friez tipping bucket gage with a totalizing counter was located at the radar site.

A simple hail indicator was constructed to supplement visual records of hail occurrence (fig. 20). This device separates the graupel and hail from the liquid precipitation. Liquid drops enter the gage and pass through a wire mesh. Solid particles entering the gage roll down the mesh into a receptacle placed beneath the wire mesh funnel. A metal deflector prevents rain from entering the center portion of the gage. A drip trough pressed into the screening prevents large drops from rolling along the surface of the wire mesh. The gage can be calibrated to indicate the water equivalent of melted hail in the collection receptacle.

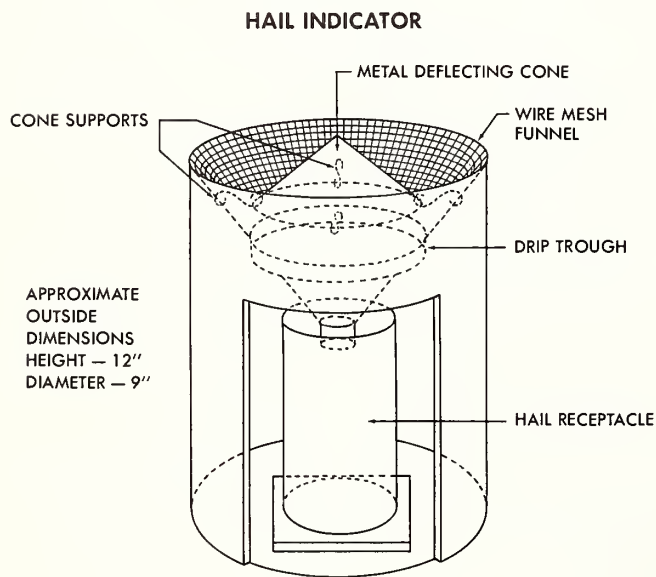


Figure 20.--Hail indicator used to supplement visual records of hail occurrence in the study area.

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